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https://revistas.ufpr.br/raega

Electronic ISSN 2177-2738
RA'EGA, Curitiba, PR, V.57, p. 3 - 22, 08/2023
http://dx.doi.org/10.5380/raega.v57i0.92335

Assessment of sandbank dynamics using high-resolution images in Areal do Limeira River, Southern Brazil

Avaliação da dinâmica de bancos de areia com imagens de alta resolução no Rio Areal do Limeira, Sul do Brasil

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http://dx.doi.org/10.5380/raega.v57i0.92335

Abstract

The river deposition dynamics is determined by its transport capacity and volume of sediments available in the drainage channel. Such changes in this dynamic can be indicative of an environmental disturbance, and its assessment can assist the territorial planning, management, and ordering. Therefore, this study aims to analyze the dynamics of sandbanks in the Areal do Limeira River, between the years 2009 and 2020, by using high spatial resolution satellite images. The methodology consisted in the use of a series of RapidEye images for the visual vectorization on the image of the sandbanks in the Areal do Limeira River watershed. Subsequently, the data was tabulated, analyzed, and compared with the rainfall volume and land use aspects. There was a higher occurrence of sandbanks between 2009 and 2012, coinciding with the implementation of forestry plantations in the study area, followed by a sharp decline until 2015, and a small increase and stabilization in the following years, when the forestry plantations reached their mature stage. In general, the use of high-resolution images has allowed for the identification of fluvial sandbanks, with adequate precision and quality.

Keywords:
Fluvial Dynamics, Remote Sensing, Silting.

Resumo

A dinâmica de deposição dos rios é determinada pela capacidade de transporte e o volume de sedimentos disponíveis no canal de drenagem. Por vezes as mudanças nesta dinâmica pode ser um indicativo de desequilíbrio ambiental, cabendo a sua análise para auxiliar no planejamento e ordenamento territorial. Desta forma, o trabalho tem como objetivo analisar a dinâmica dos bancos de areia no Rio Areal do Limeira entre os anos de 2009 a 2020 com o auxílio de imagens de alta resolução espacial. A metodologia consistiu no uso de uma série de imagens RapidEye, para a vetorização através de interpretação visual sobre a imagem dos bancos de areia na Bacia Hidrográfica do Rio Areal do Limeira. Posteriormente os dados foram tabulados, analisados em

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função da dinâmica temporal. Houve uma maior ocorrência de bancos de areia entre os anos de 2009 e 2012, coincidindo com a implementação da silvicultura na área de estudo, seguido de uma acentuada queda até o ano de 2015, e uma pequena alta e estabilização nos anos seguintes, quando as plantações de silvicultura estavam em fase mais madura. De modo geral, a utilização de imagens de alta resolução permitiu identificar os depósitos arenosos fluviais, com uma precisão e qualidade adequados.
Palavras-chave:
Dinâmica Fluvial, Sensoriamento Remoto, Assoreamento.

I. INTRODUCTION

The environment is in constant transformation caused by natural processes or by anthropic interventions. The dynamics of erosion and deposition of rivers is determined by the water velocity and its transport capacity, as well as the volume and size of the sediments supplied to it (BHATTACHARYA et al., 2016). Sometimes, these transformations can indicate environmental imbalances, and the analysis of these changes becomes important to understand the active processes and assist in territorial planning and ordering (SIMENSEN et al., 2018; YANG et al., 2020).

In order to understand the dynamics of sandbanks in rivers, measuring points are commonly used to measure and model shear stress and roughness, water velocity and volume, drainage channel morphology, and sand granulometry measurements at different points of the river (GERALD, 1967; MUELLER et al., 2005; VERICAT et al., 2008; NEUHOLD et al., 2011; FAGHERAZZI et al., 2015). However, the use of satellite images to help monitor sandbanks has increased, as it allows for greater spatial and temporal coverage at low cost (TEOTIA et al., 2009; SOUZA E REIS, 2011; STRICK et al., 2019; BLASCO et al., 2020).

Several remote sensing products have shown potential to assess the dynamics of sand dunes with data from synthetic-aperture radar (SAR) (ŁABUZ, 2016; BLASCO et al., 2020), fraction of sand in soil quantification (SALISBURY et al., 1992; HUETE et al., 2003; BREUNIG et al., 2008; BREUNIG et al., 2009), and river sandbank studies (CARBONNEAU et al., 2006; CARBONNEAU 2018; STRICK et al., 2019). The RapidEye constellation launch represented a milestone in the generation of images with high spatial resolution and high repeatability (RAPIDEYE, 2012). With available data since 2009, a large database was created and complemented with the PlanetScope constellation, with more than 150 3U (10/10/30 cm) (PLANET TEAM, 2020, 2019). Just as the Landsat program historical series, with more than 50 years, is distinctive (MASEK et al., 2020), the RapidEye database is unique, given its spatial and temporal refinement. Despite this data potential against the median

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spatial resolution of Landsat (MASEK et al., 2020) and Sentinel-2 MSI (DRUSCH et al., 2012) data, few studies have been developed to assess the dynamics of Brazilian river sandbanks (VIEIRA et al., 2017).

In southern Brazil, the occurrence of accelerated erosion and the development of large gullies have caused significant soil degradation and decreased fertility (ROBAINA et al. 2002; ROBAINA E TRENTIN, 2004; CABRAL, 2004; CABRAL, 2018; RADEMANN, 2019). Furthermore, a land use dynamic is marked by the alternation in the use of fields with native vegetation, agriculture, and forestry (SILVA, 2012; RADEMANN et al. 2019) and has led to an aggradation of the drainage channels in the region (CABRAL, 2004; SUERTEGARAY, 2012).

Considering the land use dynamics in recent decades and the erosion issue in the study area, it is important to study its impact on water bodies. Therefore, the purpose of this study is to evaluate the dynamics of the sandy deposits that occur on the banks of the drainage channels of the Areal do Limeira River by using a temporal series of images from the RapidEye constellation between the years 2009 and 2020. The relationships between the deposition area and the rainfall regime and the changes in land use and occupation that occurred during the studied period were explored.

Study Area

The Areal do Limeira River watershed (BHAL) is located in the central portion of the municipality of Cacequi, in the southwest of Rio Grande do Sul state, Brazil (Figure 1), has a total area of 71.14 km², comprising a relief of transition between hills and plains (RADEMANN et al., 2016). At the mouth of the watershed, the altitude is 92 meters, and in its highest portion it reaches altitudes up to 190 meters, resulting in a 98-meter altimetric amplitude. The hills, located in the upper portion of the watershed, have slopes ranging from 5 to 15%, with a maximum slope value of 52%. The plain areas have slopes up to 2% and are associated with the lower parts of the watershed and the main drainage channel. In general, the study area has mean slopes around 6.9%, which is typical for a slightly undulating relief (RADEMANN; TRENTIN, 2018).

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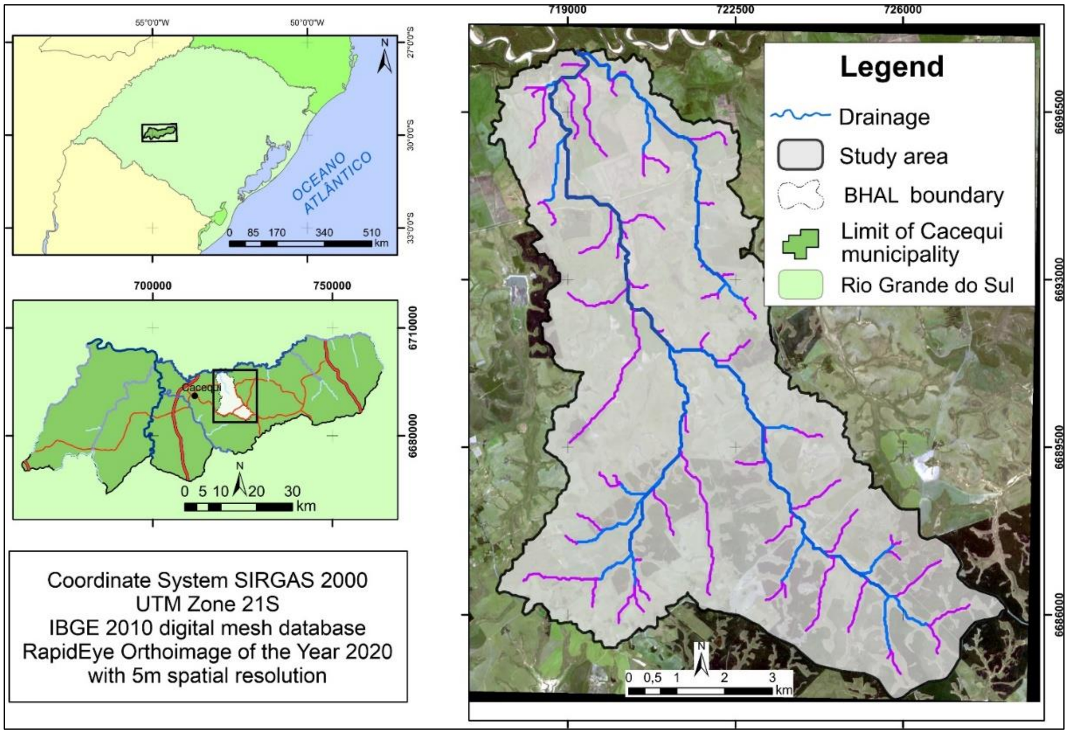

Figure 1 – Location of the study area in southwest of Rio Grande do Sul, Brazil. (The authors, 2023)

Areal do Limeira River has a 1.25 sinuosity index, and the basin as a whole has a 1.43 km/km² drainage density (RADEMANN, and TRENTIN, 2015). The BHAL is characterized by the occurrence of sandbanks of significant magnitude in the drainage channels, with variations in size and concentration over time. The lithologies are divided into Pirambóia Formation, in the upper portion, and current alluvial Deposits and Colluvium in the lower portion of the basin (CPRM, 2006). The region's climate is defined as Cfa, subtropical with hot summers, according to the Köppen-Geiger classification (KOTTEK et al., 2006; ALVARES et al., 2013), where precipitation is well distributed throughout the year, ranging from 1,600 to 2,200 mm (ALVARES et al., 2013).

II. MATERIALS AND METHODS

RapidEye images were generated by RapidEye Earth Imaging System (REIS) sensors and acquired from the PlanetExplorer repository (Planet Team, 2020). These sensors generated images for the Blue (440-510 nm), Green (520-590 nm), Red (630-685 nm), Red-Edge (690-730 nm), and Near Infrared (760-850 nm) bands. Data was acquired with radiometric and atmospheric correction applied by the ATCOR3 model (Richter, 2007). The original spatial resolution is 6.5 meters, and, after orthorectification, the bands are resampled to 5 m resolution,

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resulting in corrected images with a precision of detail compatible with a 1:25,000 scale. It is believed to be suitable for assessing sandbanks in the study area.

True (RGB) and false (IVRG) color compositions were used for image interpretation from the years 2009 to 2020, where the deposition banks were identified and vectorized over the image throughout the entire extension of the Areal do Limeira River basin. Image dates were chosen according to the availability of good quality images without cloud cover. Thus, an image was selected for each analyzed year, approximately from the same period of the year, corresponding to the summer (Dec – Mar).

To describe the dynamics of precipitation in the period from 2009 to 2020, reprocessed data from the "Time Series, Area-Averaged of Precipitation Rate monthly 0.25 deg. (TRMM TRMM_3B43 - TRMM 3B43: Monthly Precipitation Estimates) and Time Series, Area-Averaged of 2-meter air temperature monthly 0.5 x 0.625 deg. [MERRA-2 Model M2IMNXASM v5.12.4] Cover 2009-Jan - 2020-Dec, Region 54.8602W, 29.7894S, 54.7394W, 29.6906S was used (GIOVANNI/NASA, 2021). In the relationship between precipitation and sandbanks, data referring to the months of January, February, and March were used aiming to approximate the accumulated precipitation in the period close to the date of the analyzed images.

Data Analysis

The delimitation and quantification of the sandbanks was carried out via manual vectorization (Supervised), based on the color composition of true color and false color. Next, area, perimeter, and centroid information was generated for each sandbank in each year studied. Sandbanks were divided into three classes: smaller than 0.1 ha; from 0.1 to 0.5 ha; and larger than 0.5 ha. The detailed analysis of some areas of the watershed was carried out in the most traditional scenario period of 2009, where the region had the predominant use of fields associated with extensive cattle raising, as well as the dates of 2012, 2015, and 2020, periods in which the study area underwent transformations in land use with the implementation and development of forestry.

Variations in this data were analyzed over the study period and compared with precipitation information. The crossing of information on changes in the quantitative and qualitative parameters of the sandbanks with the precipitation data was analytically carried out in the Origin 2021 software.

Aiming to assist in understanding the drivers of change in sandbanks, information was collected through fieldwork conducted from 2014 to 2019 on five different occasions, with descriptive and photographic surveys and aerial surveys, where the occurrence of linear erosion processes and land use and land cover change were observed.

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III. Results and Discussion

This item presents the analysis and discussion of the data obtained in the research. It starts with the morphometric and climatic characterization, followed by the analysis of the sandbanks and a discussion of the relationship with the climatic data and aspects of land use and land cover in the area.

Watershed rainfall characterization

The Areal do Limeira river basin has a total area of 71.14 km², comprising a relief of transition between hills and plains (RADEMANN et al., 2016). In the upstream portion of the basin, hill units predominate, while closer to the mouth, the fluvial plain of the Ibicuí river predominate. At the mouth of the watershed, the altitude is 92 m, and in its highest portion it reaches altitudes up to 190 m, resulting in a 98-meter altimetric amplitude.

The climate in the study area, according to Rossato (2011), is characterized by the predominance of polar systems (45 – 48% of the days of the year), where the frontal systems are responsible for most of the precipitation. Annual rainfall ranges from 1,500 – 1,700 mm, and temperature annual means range from 17 – 20°C. Temperatures fluctuate throughout the year, with lows in winter, mainly in June and July, and highs in summer, in December and January.

In the period from 2009 to 2020, there was a mean monthly precipitation of 163 mm, with some months of higher precipitation, as in the case of November 2009, exceeding 600 mm of rain (Figure 2). Intense rainfall events and high levels of accumulated precipitation are essential for the loading of sediments and, therefore, have a great impact on the river sandbank dynamics. During the evaluated period, 11 months were identified with accumulated precipitation greater than 300 mm. Some dates are indicated and will be discussed based on their potential impact on sand deposition/transport.

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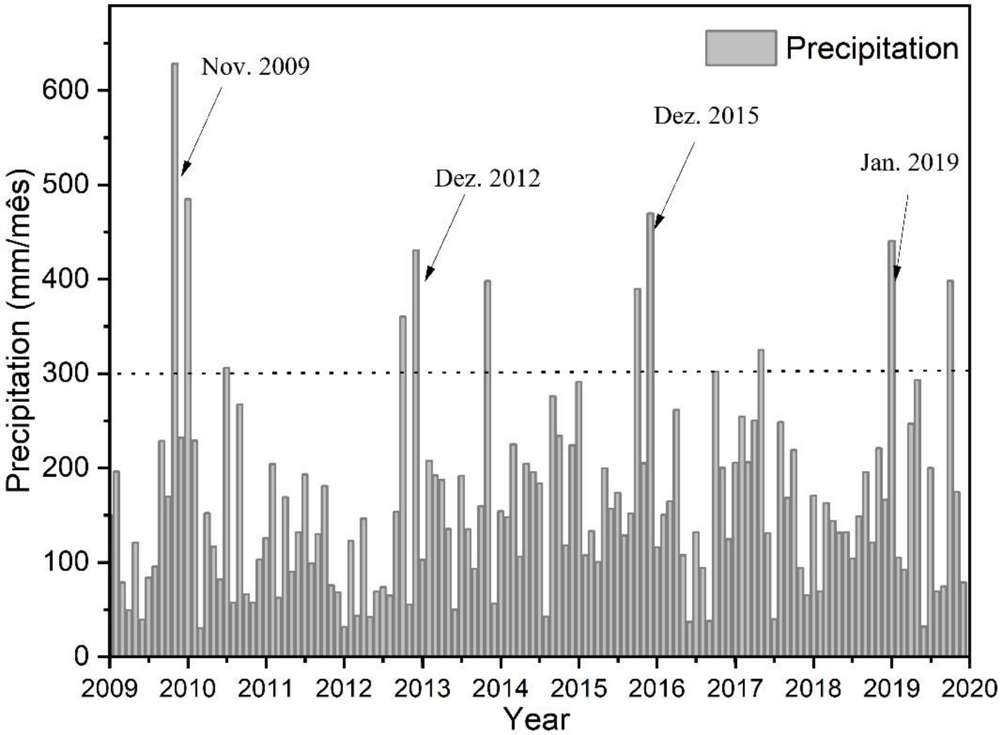

Figure 2 – Evaluation of accumulated monthly precipitation for the period from 2009 to 2020. The dotted line indicates the cumulative rainfall threshold of 300 mm/month. Some dates are indicated as high precipitation events. (The authors, 2023)

Land use and land cover dynamics: The implementation of forestry

From 2004 onwards (SILVA, 2012), with the entry of pulp and paper companies in southern Brazil, most of the field areas were occupied by forestry, as in the case of the Areal do Limeira River basin. The areas chosen for the plantation of exotic species were those with the greatest environmental fragility, due to their lower price, such as the areas where gullies occur (MARCHIORI and ALVES, 2010; SUERTEGARAY and MORELLI, 2010) as shown in Figure 3.

Figure 3 – Association of forestry and large gullies in the study area. (The authors, 2023)

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RA'EGA, Curitiba, PR, V.57, p. 3 - 22, 08/2023
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Eucalyptus planting in the study area rose 268% between 2009 and 2012 (from 303.33 hectares to 1,188.62 hectares, respectively), as shown in the Figure 4 map.

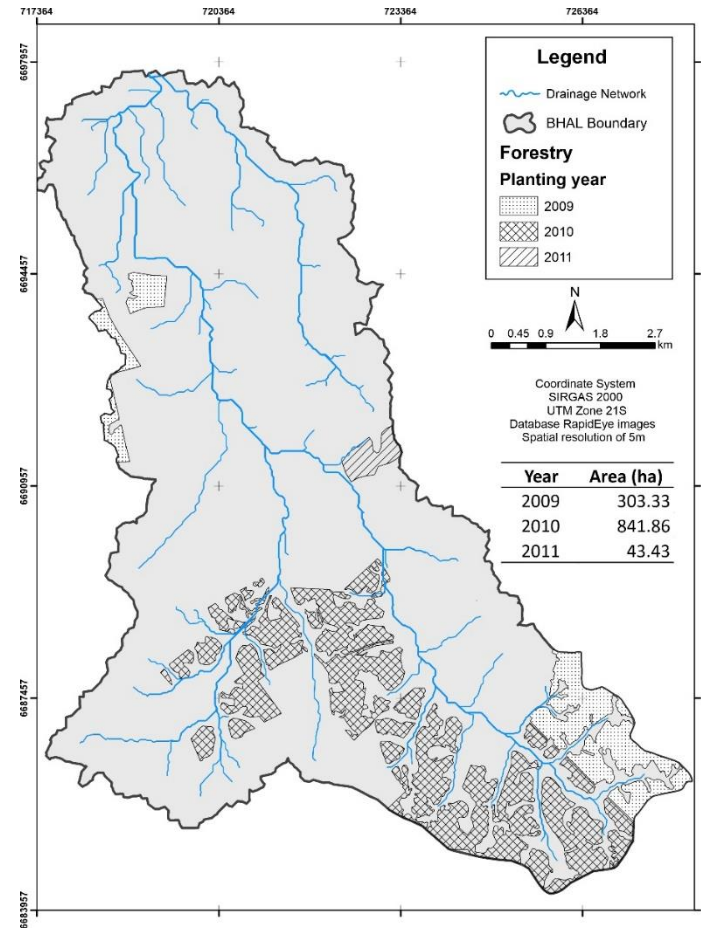

Figure 4 – Map of the year of forestry planting in the Areal do Limeira river basin (BHAL) between the years 2009 and 2011. (The authors, 2023)

Analysis of sandbanks

Through the temporal variation analysis of the sandbank in the study area we can state that there is a predominance of deposition areas smaller than 0.1 ha, with mean 54.83 deposits/year during the studied period. In general, 2012 was the year with the largest total area of sandbanks, with 23.60 ha (Table 1), and the year 2015 was the year with the smallest area of occurrence (13.28 ha).

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Table 1 – Variation in the area and number of sandbanks between 2009 and 2020, annually mapped from RapidEye images.

Year	Total deposition area (ha)	Number of deposition areas up to 0.1 ha (unit)	Deposition areas up to 0.1 ha (ha)	Number of deposition areas between 0.1 and 0.5 ha (unit)	Deposition areas between 0.1 and 0.5 ha (ha)	Number of deposition areas > 0.5 ha (unit)	Deposition area > 0.5 ha (ha)
2009	23,39	52	2,96	56	12,61	10	8,23
2010	21,93	79	3,16	49	11,28	8	7,49
2011	20,61	52	2,70	52	11,15	9	6,76
2012	23,60	39	2,23	54	12,96	11	8,41
2013	22,05	30	1,63	57	12,94	8	7,48
2014	17,52	61	2,49	47	11,84	4	3,18
2015	13,28	32	1,87	37	8,41	4	3,00
2016	19,31	95	4,03	54	11,73	5	3,55
2017	15,44	59	2,62	44	9,94	4	2,88
2018	18,39	40	2,04	38	8,84	8	7,51
2019	17,08	59	2,37	53	12,77	3	1,94
2020	17,89	60	2,96	40	9,53	6	5,40
Mean	**19,21**	**54,83**	**2,59**	**48,42**	**11,17**	**6,67**	**5,49**

(The authors, 2023)

During the 2009 to 2011 period, there was a slight downward trend in deposition areas, followed by a sudden increase of 14.5% in 2012, when the greatest record in sandy deposits occurred. From 2012 to 2015, when it reached the minimum area values, there was a 77.68% reduction of these areas. Between 2015 and 2016 there was, again, an increase in the deposition areas of about 31%, and from this year the areas remained stable until the year 2020, showing small variations over the years.

Data Discussion

The relationship between the deposition area temporal dynamics and the mean variation in precipitation was evaluated, considering that events with a large volume of rainfall can lead to acceleration of erosion and, consequently, deposition downstream (LIU et al., 2020; MORGAN, 2005). In the study area, there was no relationship between mean precipitation and deposition areas, as observed in Figure 5. In general, precipitation in the studied periods was irregular, with a quarterly mean around 470 mm, with precipitation peaks in the years 2010 (744 mm), 2017 (666 mm), and 2019 (637 mm), which did not reflect a noticeable change in the study of sandbanks during the image analysis.

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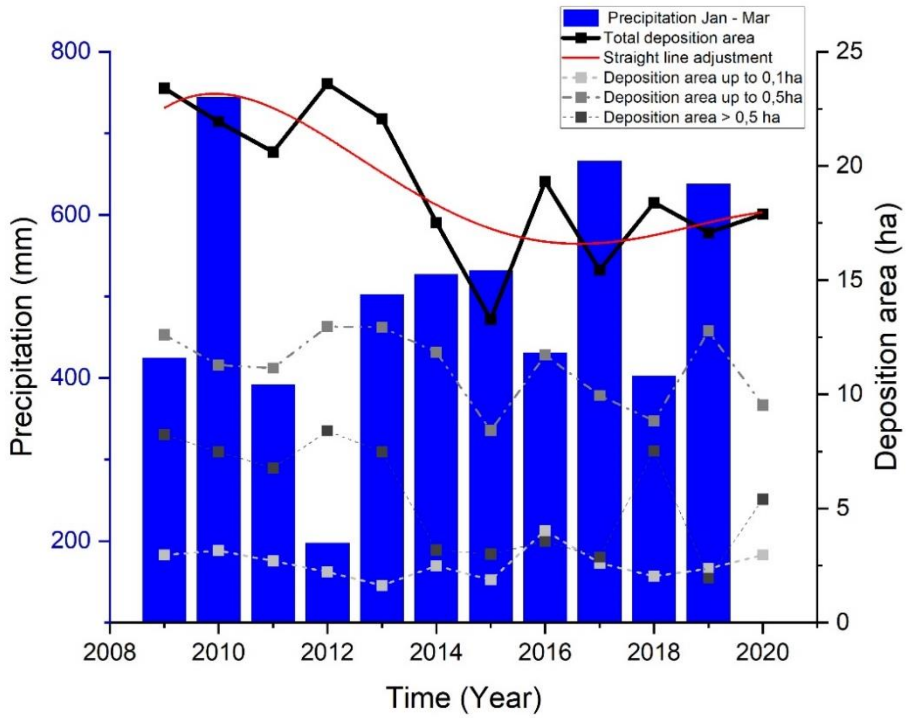

Figure 5 – Relationship of deposition areas and rainfall between 2009 and 2020 for the months of January to March. (The authors, 2023)

When comparing the change in land use, in the analyzed series, with the implantation of eucalyptus forests, differences in the evolution of sand deposits are observed in the different portions of the study area. In an area next to the main channel, in 2009, two large deposition areas were observed, one on each side of the main channel, adding up to approximately 2.55 ha of area (Figure 6). In 2012, in this same location, there was a large increase in the deposition area (about 93%) mainly on the left side of the river and a small decrease in the feature on the right side, totaling 4.92 ha.

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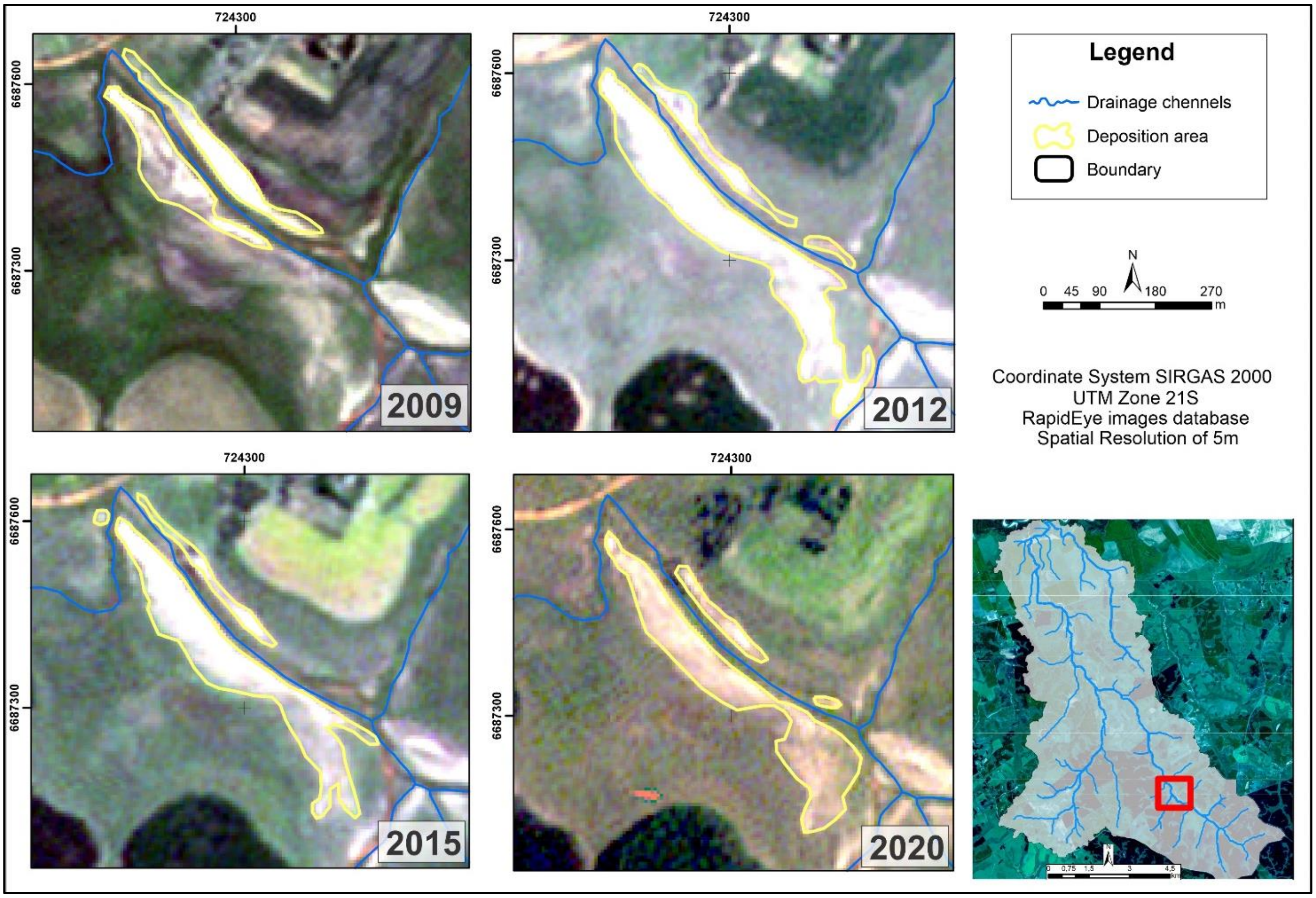

Figure 6 – Fluvial deposition next to the main channel. (The authors, 2023)

The analyzes indicate that the increase in the deposition areas upstream of the basin may be related to the planting of eucalyptus trees in the study area, whose concentration increased by 268% between 2009 and 2012 (from 303.33 hectares to 1,188.62 hectares, respectively). In the following years there was a decrease in sandbanks, about 23%, reaching 3.77 ha in 2020. This decrease occurred homogeneously in this portion of the study area, with the reduction of existing banks, and may be associated with the stabilization of slopes by soil cover and root action.

Next to a tributary of the Areal do Limeira river, close to an area where gullies occur, the development of sandbanks was similar to that found near the main channel, where there was a large increase in the deposition area between 2009 and 2012, but even more significant, 752% (Figure 7). This tributary has a significant number of large gullies associated with its upstream slopes. During this period, large-scale eucalyptus plantations may have accelerated the erosion of these features and contributed to the large increase in sand deposits in the area. In general, forest plantations tend to generate greater impacts on the quantity and quality of water at the

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watershed level in the initial years of implantation, given the greater action on the soil (e.g., tilling, pits, cleaning, machine traffic, etc.) (PERRANDO et al., 2021).

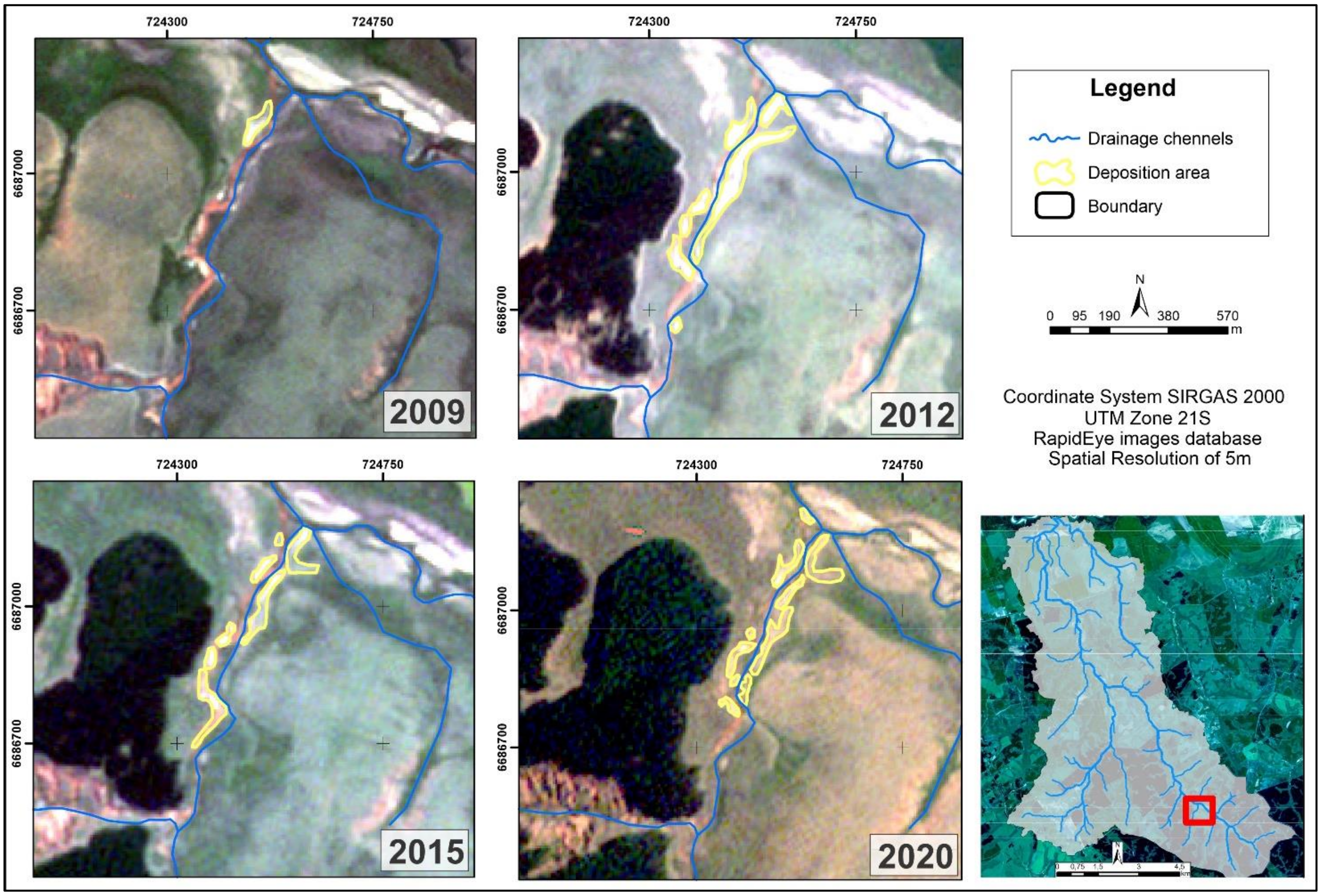

Figure 7 - Fluvial deposition in an affluent close to the occurrence of gullies. (The authors, 2023)

Subsequently, in 2015, there was a decrease about 30% in the total area of sand deposits, and in the following years, until 2020, there was a stability trend, with a small 3% increase. Although in the period from 2009 to 2012 the forestry implementation contributed to the increase in sand deposits in this area, from 2012 onwards, when the trees showed greater vegetative development, they tend to produce litter on the soil, induce containment by barriers, and usually in association with an understory, there is a decrease in erosion, which may have caused a decrease in deposit areas in this period.

In the lower portion of the watershed, close to the Ibicuí river, deposition areas remain close to the drainage channel (Figure 8). The deposition areas at the beginning of the time series, in 2009, corresponded to a 2.68 ha area mainly formed by sandbanks between 0.1 and 0.5 ha. In 2012, there is a large increase in the deposition area (44%) to 4.84 ha and an increase in the mean size of sand banks. As in the other watershed areas, between 2012 and 2015 there was a sharp decrease in the deposition areas in this area, about 44% (a 1.47 ha decrease). From 2015 to 2020, there was again an increase in the deposition areas, about 27% for 4.67

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ha, pointing to an increase in erosion upstream. It should be noted that precipitation remained similar throughout the analyzed period, with extreme events before and after the reduction in area rand number of sandbanks.

Figure 8 – Fluvial deposition in the lower course of the study area. (The authors, 2023).

Overall, throughout the Areal do Limeira river basin there was a small decrease in the deposition areas between the years 2009 and 2011, an increasing peak in the year 2012, followed by a decrease in the total area until the year 2015, and then a relative stabilization in subsequent years. The increase that occurred mainly between 2009 and 2012 can be related to land use in the study area, where there was a significant change in a large part of the watershed area, especially in the upper portion of the basin. During this period, there was a 291% increase in eucalyptus areas occupying fields and crops, which in the planting process can contribute to increased erosion. However, the forestry implantation impact in the deposition areas was more pronounced on a local scale, having a great impact on the areas adjacent to the new plantations and not reflecting so strongly on the total area of the basin.

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During the eucalyptus planting phase, soil preparation occurs, which, despite not being very demanding in terms of soil preparation, requires subsoiling with a 40 to 60 cm depth, which consists of breaking the surface layers of the soil to facilitate root formation. Another procedure often used in eucalyptus forestry after planting is cleaning the area and removing weeds around the seedlings to eliminate competition (WILKLEN et al. 2008, PEZZATO, et al. 2016).

These subsoiling and removal of much of the vegetation procedures can contribute to erosion. The breakage of the surface layers, and consequently the disintegration of the soil, helps to reduce the soil's resistance to erosion, facilitating the loading of soil particles. On the other hand, the removal of vegetation, which can be considered the soil natural defense against erosion (BERTONI and LOMBARDI NETO, 2012), decreases the soil protection against the impact of raindrops and decreases the soil infiltration capacity (GALETI, 1984; BIGARELLA, 2003; PRUSKI, 2009; BERTONI and LOMBARDI NETO, 2012).

Eucalyptus forestry, when it reaches a more advanced stage, requires less care and with less impact on the soil, with thinning and pruning being the main necessary management practices that, when the material is deposited in the plantation itself, provides organic matter to the soil, making it more resistant erosion (WILKLEN et al. 2008, PEZZATO, et al. 2016). Therefore, we could associate the decrease in the deposition areas in the study area in the years following the eucalyptus planting, when the trees developed and formed litter, which could be the main factor for the oscillations of the deposition areas close to the drainage channels of the studied area.

The rainfall analysis did not allow identifying a relationship between the increase or decrease in mean precipitation with the variation of sand fields. However, the change in use seems to have directly contributed to the surface dynamics of the area, including the increase and decrease of deposition areas.

IV. Conclusions

In general, geoprocessing and remote sensing tools, by using images with a 5-m spatial resolution, proved to be effective for the purposes of this study. The use of these tools made it possible to identify the sandy deposits at a good working scale, guaranteeing precision and quality to the generated data. The analyzes of visual interpretation of high spatial resolution images made it possible to contextualize the temporal dynamics in the data series from 2009 to 2020 regarding the occurrence of sandbanks present in the Areal do Limeira river watershed. In general, the deposition areas in the study area showed an increase dynamics between the years 2009 and 2012, followed by a gradual decrease until 2015, followed by a stabilization. This

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recorded increase refers to the occurrence areas of sandbanks. In the general context of the analyzed period, a decrease in deposition areas was observed.

The increase in these deposition areas in the period from 2009 to 2012 coincided with the implementation of forestry in a portion of the study area. Thus, presenting a relationship between the eucalyptus planting phase and the increase in erosion and, consequently, the increase in the availability of sediments for the formation of deposits in the drainage channels. Furthermore, the growth and maturation phase of the eucalyptus trees coincided with periods of reduction in sandy deposits, which remained at lower levels than before and during planting.

The study raises several questions that must be investigated through the application of different methodologies and that can support further discussions regarding the procedures to be adopted in the study area, as well as in similar areas. Changes were observed in the deposition areas, but it is worth investigating whether the material volume in these sediment banks has changed, and whether the increase in areas directly reflects the increase in volume of these areas and the opposite for the decrease in these areas. It is possible that the decrease in areas is a reflection of the decrease in surface dynamics, however, the sediment banks remained present in the study area, but covered by vegetation, which would mask their identification, requiring further research.

A future analysis of other parameters that influence erosion, in addition to land use and absolute precipitation, may lead to other possibilities for interpreting these variations in sand deposits, with their investigation being of great importance, as well as a more detailed investigation of sand banks with their volume analysis. Also, the sandy deposit material analysis – allowing this material origin to be identified – will be able to help understanding the dynamics of these deposition areas.

Acknowledgements

The authors thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq, process 305084/2020-8; process 300975/2019-8; process 302996/2021-4) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the financial support. They thank the Universidade Federal de Santa Maria (UFSM) for the research space and support and Planet Labs for the high-definition RapidEye Images availability (Education and Research Standard – ID 503533).

ISSN eletrônico 2177-2738
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